An Overview of the Center for Bio-Optoelectronic Sensor Systems (BOSS)

DARPA Optoelectronic Center Kickoff Meeting
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Presented by
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Contract Title: *MDA972-00-1-0021*

Center for Bio-Optoelectronic Sensor Systems
Agenda

- Overview (20 m.)
  - Norman Cheng (U. of Illinois-Urbana-Champaign)
- Task 1: Micro-spectrometer-based vapor bio-sensor systems (30 m.)
  - Russ Dupuis (U. of Texas-Austin)
- Task 2: Interferometer-based aqueous bio-sensor systems (30 m.)
  - Kevin Lear (Colorado State U.)
- Task 3: Heterogeneous integration (20 m.)
  - K. C. Hsieh (U. of Illinois-Urbana-Champaign)

Chemical-Biological Warfare Threat Detection and Identification Methods

Biological → Chemical

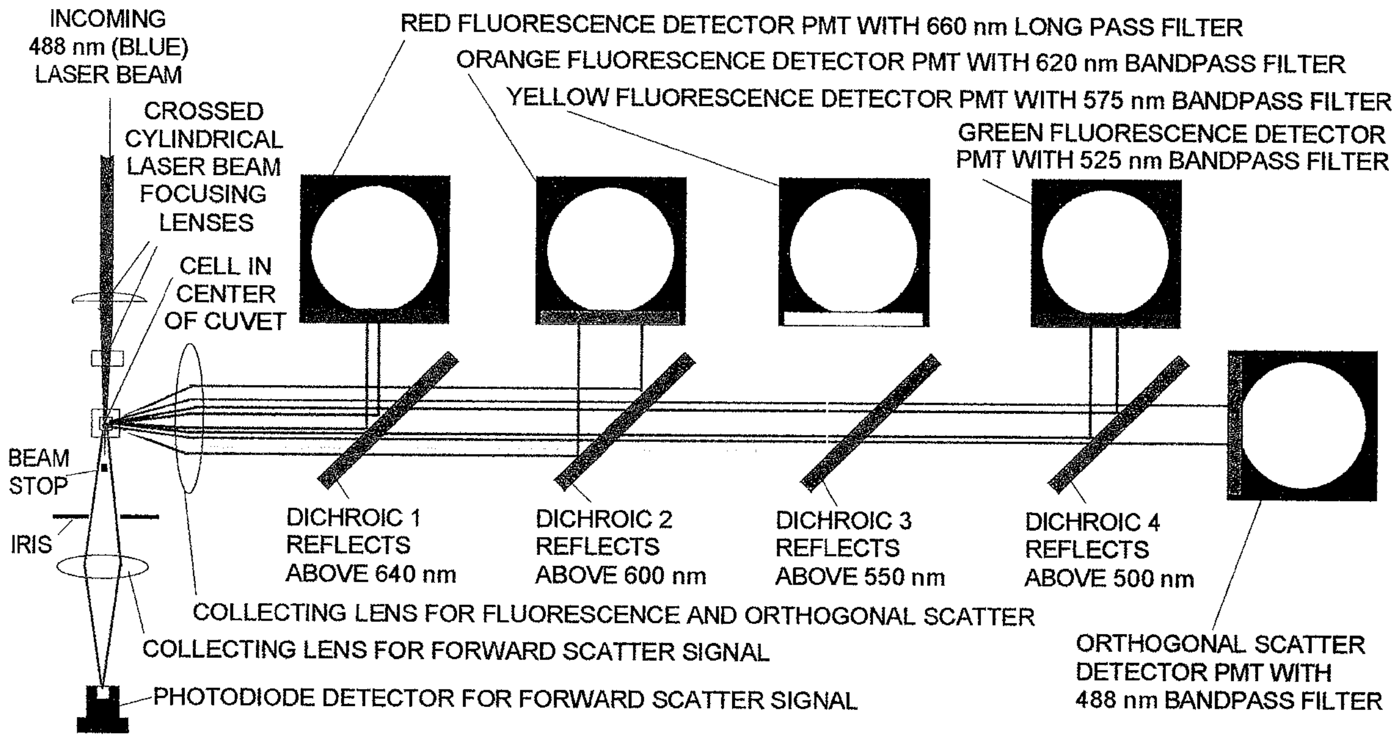
Bacteria	Rickettsiae	Viruses	Toxins	Chemicals
Anthrax	Typhus	Yellow Fever	Botulinum Toxins	Sarin
Plague	Spotted Fever	Dengue Fever	Mycotoxins	Soman
Rabbit Fever	Q-Fever	Influenza	Staphylococcus	Mustard
Diptheria			Saxitoxin	

- MALDI-TOF Mass Spectrometer
- **Flow cytometry**
- Polymerase chain reaction
- Whole-cell immunosensors
  - Colormetric
  - **DNA-based**
  - **Particle tag-based**
  - Gravimetric
  - Electrochemical

- Mass spectrometer
- 2D gel electrophoresis
- Immunosensors
  - **DNA – based**
  - Colormetric (ELISA)
  - Nanoparticle tag
    - **Quantum dot**
    - **Upconverting phosphor**
  - Gravimetric
  - Electrochemical

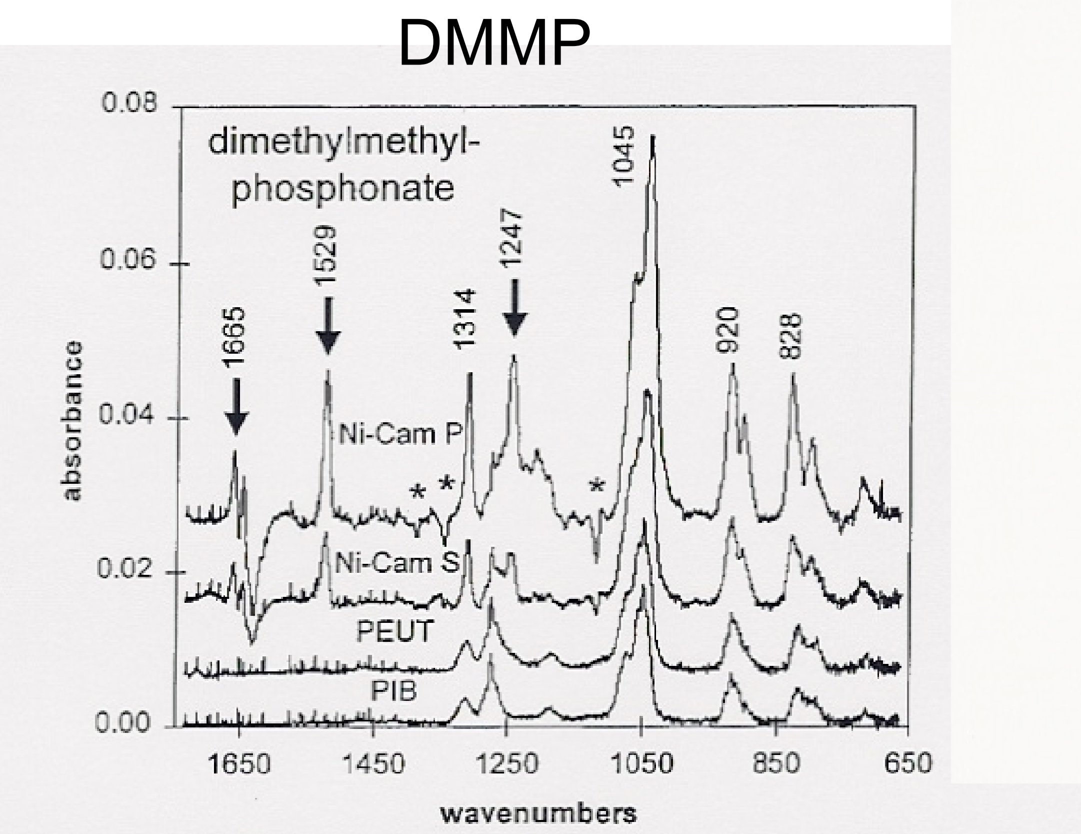
- Ion mobility spectrometer
- Mass spectrometer
- SAW sensor with sorption coating
- FPW sensor with sorption coating
- **FTIR**

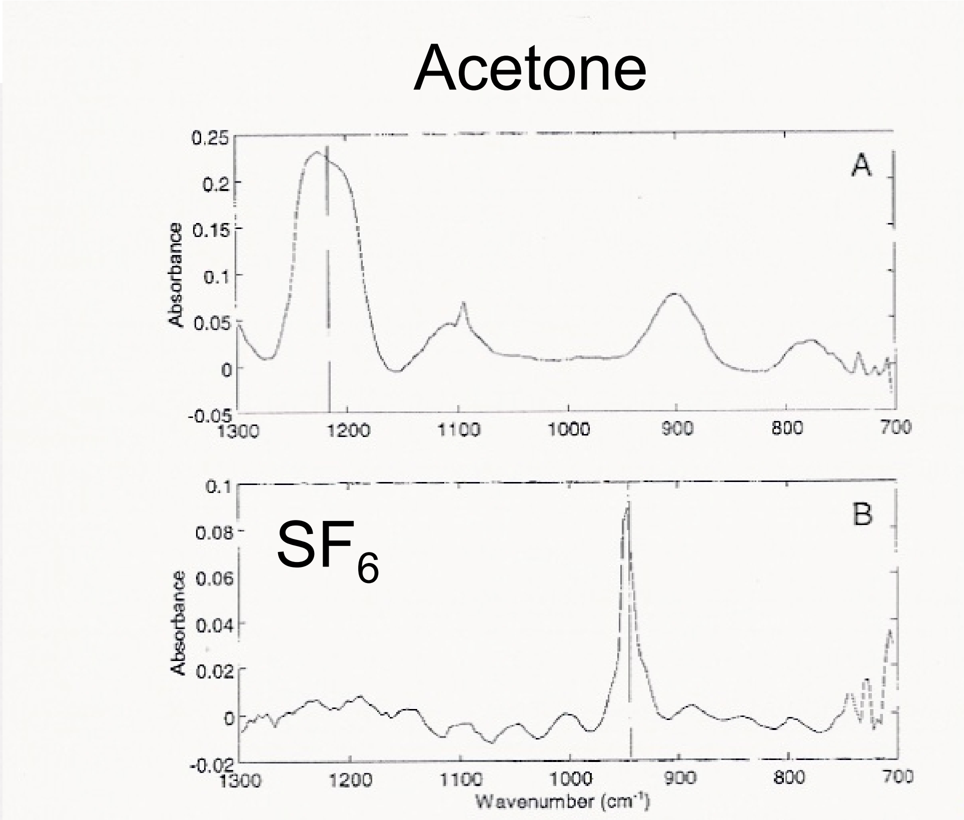
Bacteria Identification Using Flow Cytometry



- Laser excites particle within narrow “cuvet” flow chamber
- Biological agents are tagged with fluorescent-labeled antibodies
- Forward-transmitted and side-scattered fluorescent emission is observed through series of filters

IR Absorption Spectra of Chemical Vapors





- FTIR spectra are unique signatures of chemical vapor molecules used for identification

Advantages of Using Optoelectronics for Bio-Chemical Agent Sensing

- Enable compact, low cost, low power systems
- Detector photodiode can be integrated with laser
- Reduced RMS noise levels compared to gas lasers

Source: Robert Shapiro, Practical Flow Cytometry

Center for Bio-Optoelectronic Sensor Systems
Objectives

- Development of integrated optoelectronic technologies including *materials, devices, integrated interferometers, optical microelectromechanical system(MEMS) spectrometers, and components* that are critical to the realization of integrated and reconfigurable biological and biochemical sensor systems.

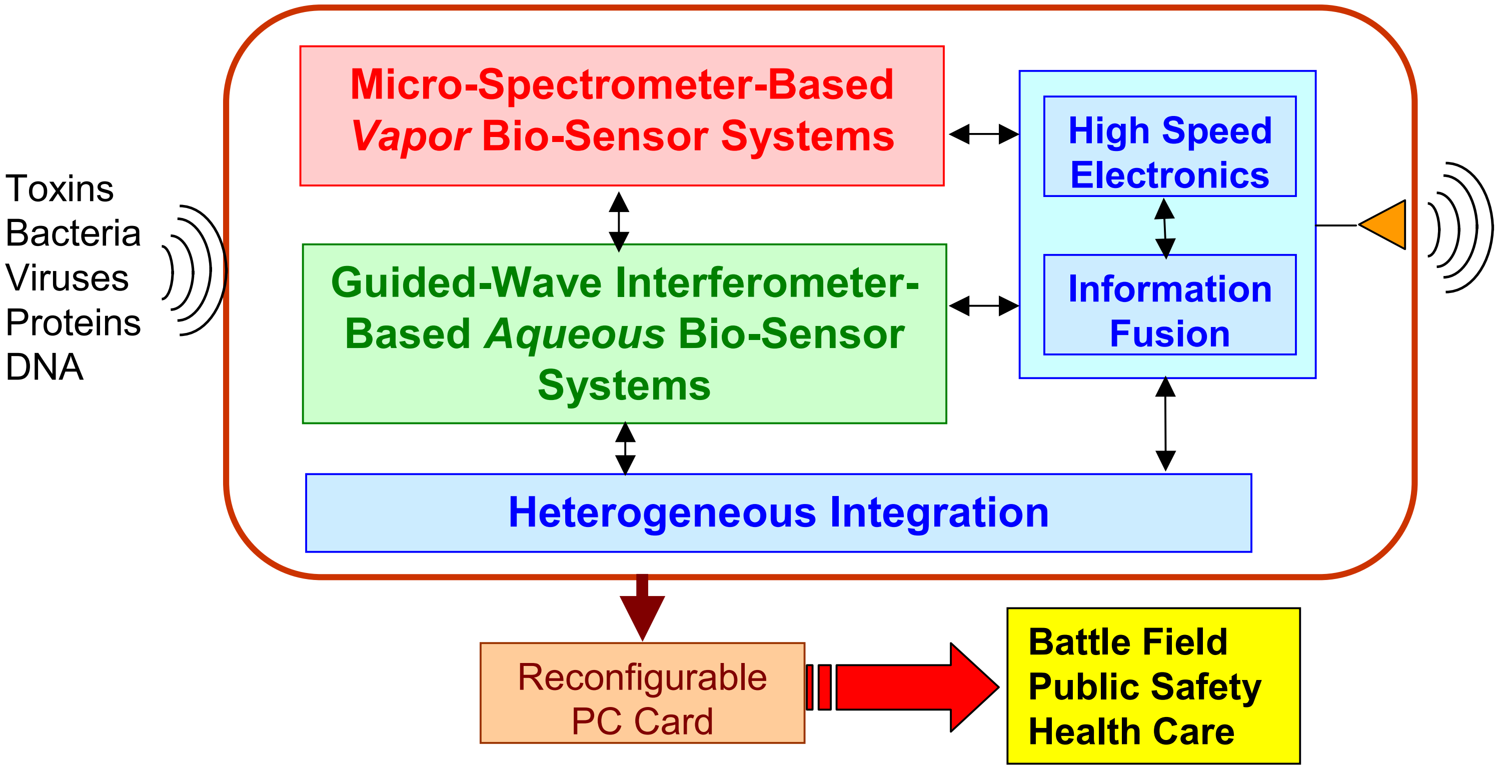
- Integration of cross-institution and cross-disciplinary collaboration to develop *light sources* from UV to mid-IR, *excitation formats*, *optical signal detecting architectures* and to *interface the optoelectronic system* with a knowledge-based signal processing unit through high-speed electronics for real-time positive identification of microbial and chemical pathogens.

Center for Bio-Optoelectronic Sensor Systems

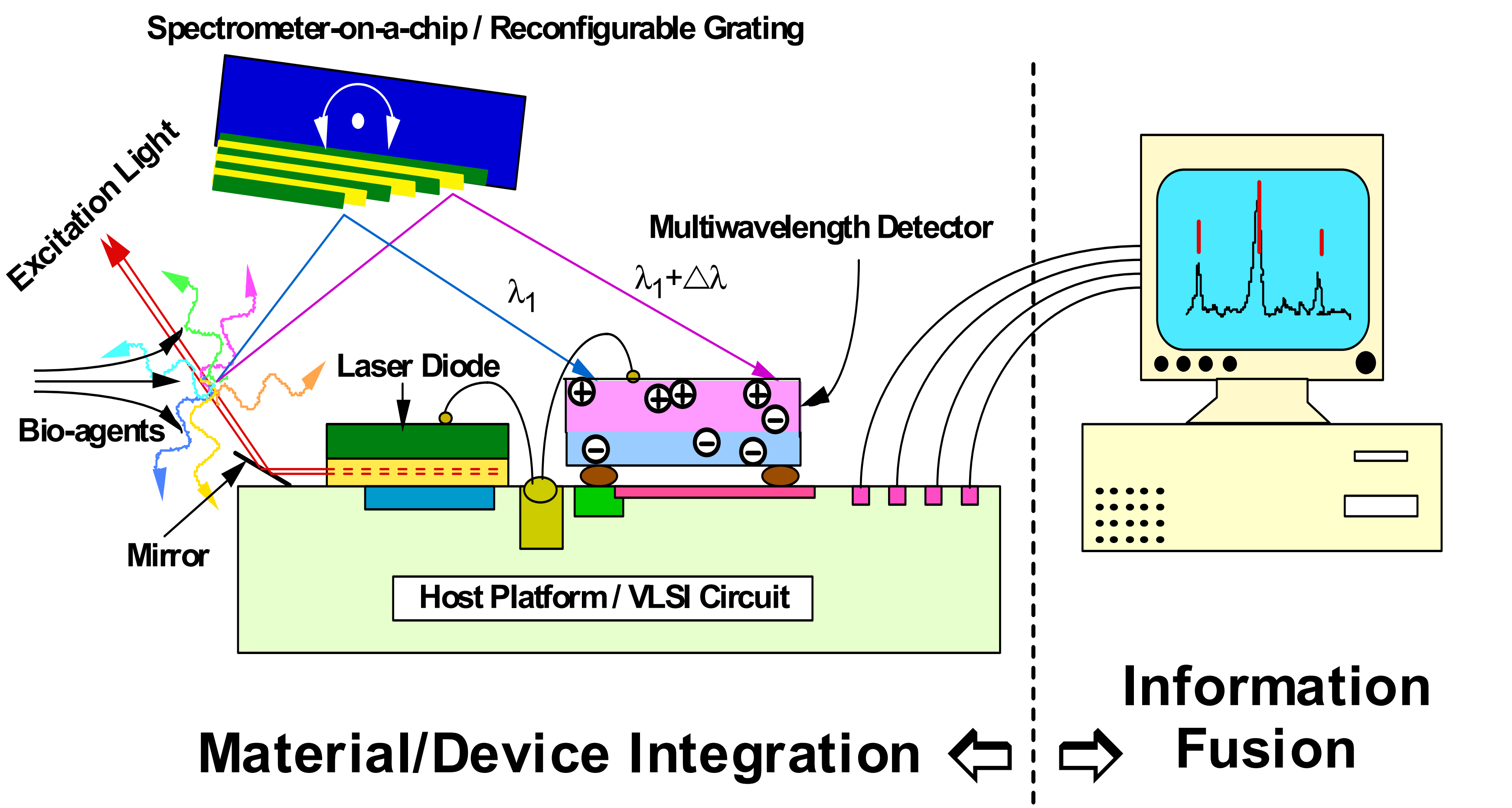
Research Vision and Approach

To develop in parallel two bio-sensor systems for

- Vapor phase agents using time- and wavelength-resolved FTIR-on-chip spectrometer and
- Aqueous agents using tunable DBR- or VCSEL-based interferometer



Biological/Biochemical Sensing System Integration



Research Personnel of the BOSS Center

Task	Team Member	Affiliation	Projects
1,3	Cheng	Illinois	Sb-based mid-IR sources/detectors
1	Chuang	Illinois	Modeling and design of mid-IR lasers and MEMS spectrometers
1	Feng	Illinois	MEMS-based gratings and optics
1	Holonyak*	Illinois	III-Nitride-based UV light source fabrication
1,3	Hsieh	Illinois	Micro-spectrometer integration, microanalysis
3	Liang*	Illinois	Bio-information fusion technology
2	Lear	Colorado State	Tunable fluidic VCSEL-based sensors
2	Wilmsen*	Colorado State	Tunable fluidic VCSEL-based sensors
1	Pinczuk	Columbia	Micro-Raman spectroscopy characterization of narrow gap materials
1	Störmer	Columbia	Low-temperature electronic characterization of narrow gap materials
1	Wang	Columbia	Sb-based mid-IR source and detector growth and fabrication
2,3	Jokerst	Georgia Tech	Interferometer-based sensor design and integration
3	Brook*	Georgia Tech	Si-CMOS and III-V components integration
2,3	Ralph	Georgia Tech	Optical characterization of interferometry sensors
2	Dagenais	Maryland	DBR laser interferometry sensors, 1.55 μm VCSELs
2	Bhattacharya	Michigan	Microfluidic photonic bandgap waveguide sensor, 1.3μm QD lasers
1	Dupuis	Texas	III-Nitride-based UV and mid-IR sources
1	Chang-Hasnian	UC Berkeley	Micro-FTIR spectrometer, optical MEMS
1	Lau	UC Berkeley	Micro-FTIR spectrometer, optical MEMS

* associate members

Center for Bio-Optoelectronic Sensor Systems

Task and Synergy

Berkeley
Columbia
Illinois
Texas

1. Micro-Spectrometer-Based Bio-Sensors

Mid-IR nitride QC lasers
Mid-IR Sb QC laser/detector
Near-/mid-IR Sb emitters
UV emitters/detectors
MEMS spectrometers

2. Interferometer-Based Bio-Sensors

DBR lasers-based sensor
VCSEL-based sensor
Micro-fluidic photonic bandgap waveguide

3. Heterogeneous Integration

Information fusion
Bioluminescence
Hybrid system integration

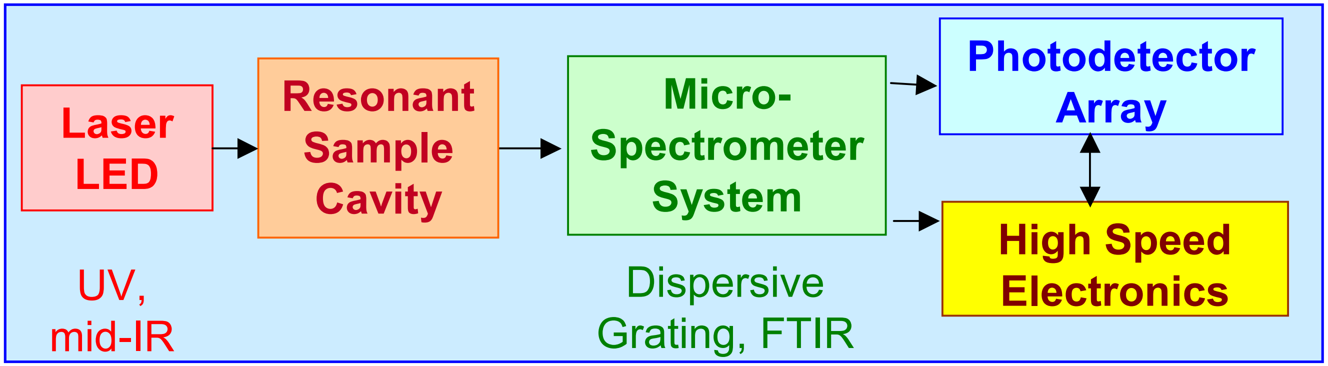
Colorado State
Georgia Tech
Maryland
Michigan

Government / Industry Laboratory

Army Research Laboratory
Draper Laboratory
US Military Academy
Agilent, LumiLeds, Lucent, Motorola
Northrop Grumman, SDL, Sensor Unlimited, Filtronics

Illinois
Georgia

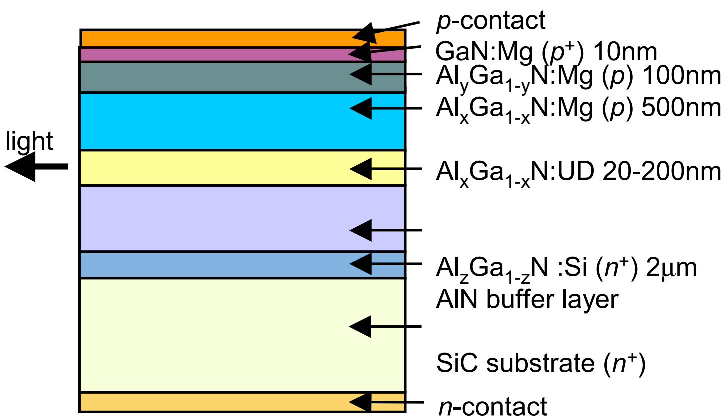
Micro-Spectrometer-Based *Vapor* Bio-Sensor Systems



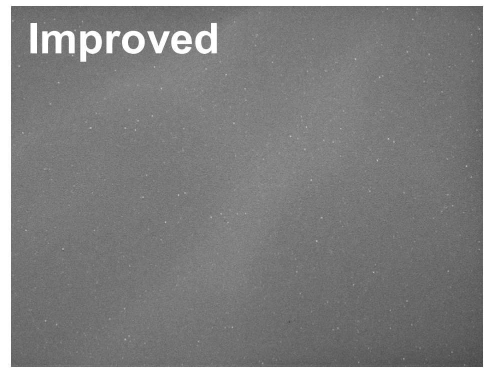
Barrier issues:

- UV laser diodes (< 300 nm).
- RT operation mid-IR laser diodes.
- UV and mid-IR detector arrays.
- Wide frequency range optical spectrometer system.

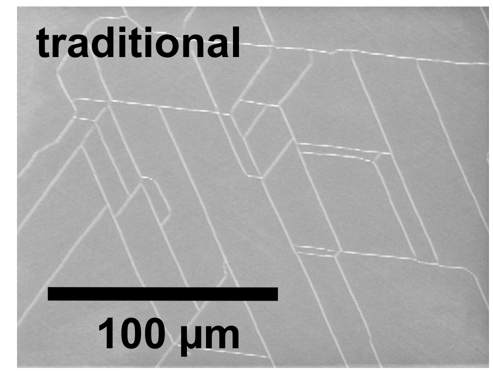
Bioluminescence Excitation :High Quality $Al_xGa_{1-x}N$ UV-Laser Structure Grown by Improved MOCVD



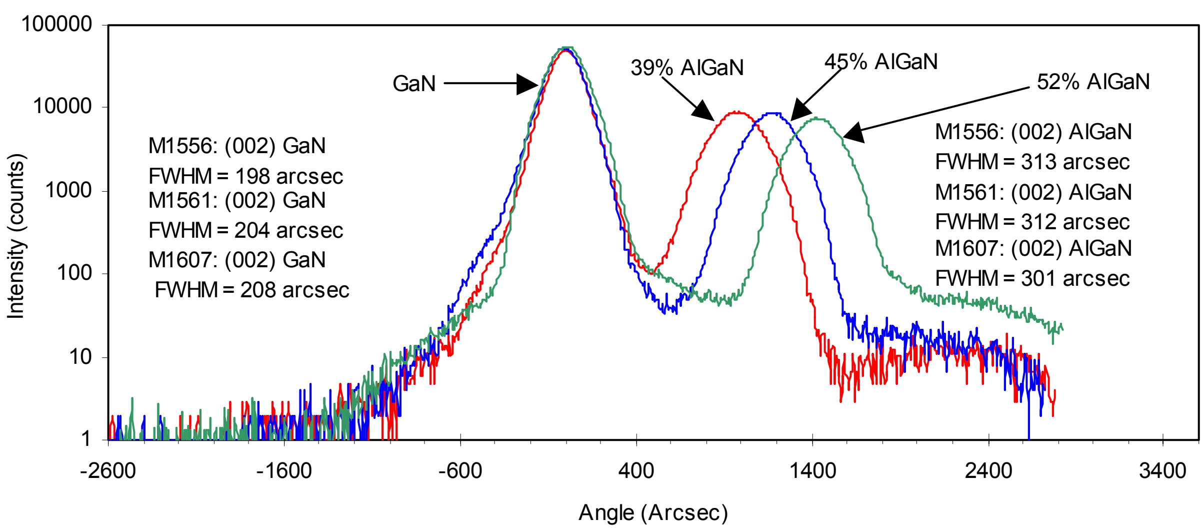
1 µm $Al_{0.5}Ga_{0.5}N/GaN$



0.2 µm $Al_{0.3}Ga_{0.7}N/GaN$

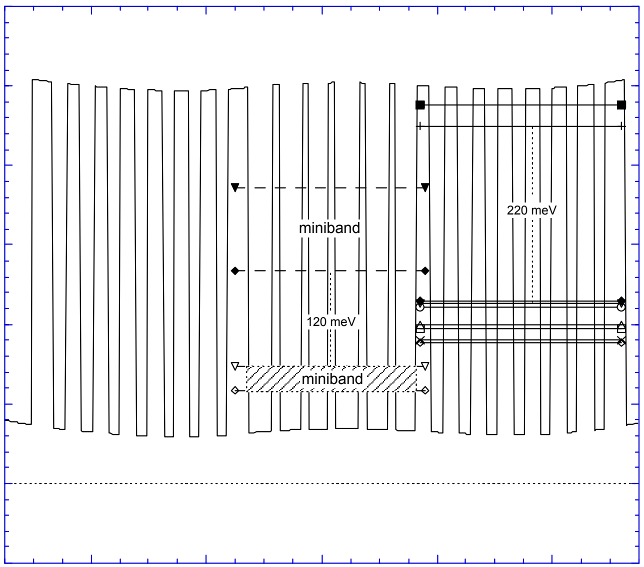


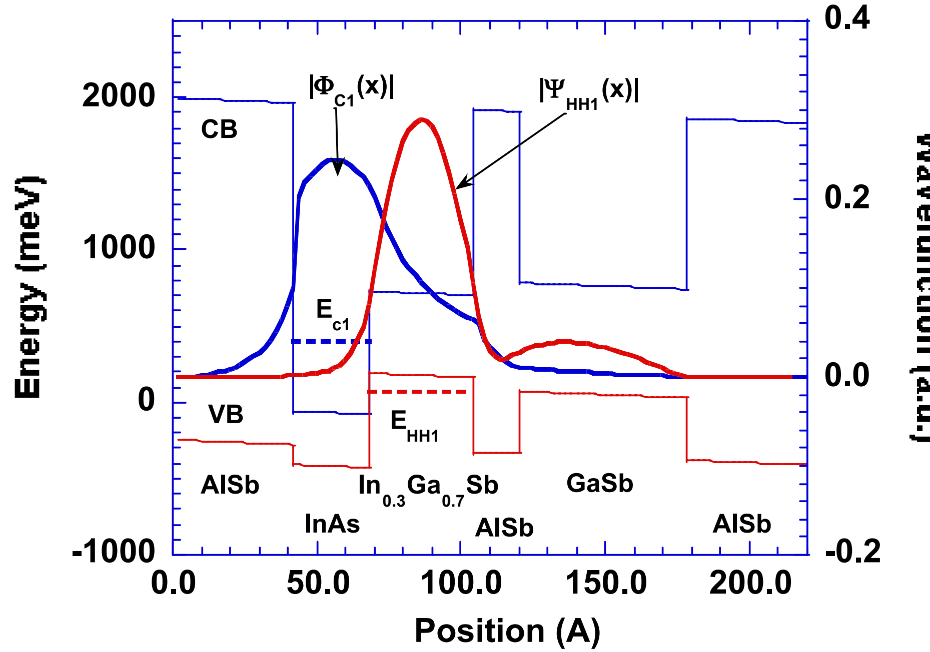
X-Ray Scan (002) Omega-2Theta



- High AlN-composition required to achieve $\lambda \leq 300$ nm
- Grown by an improved MOCVD method

Design of Nitride- and Sb-Based Mid-IR Quantum-Cascade (QC) Lasers





Nitride-based QC laser:

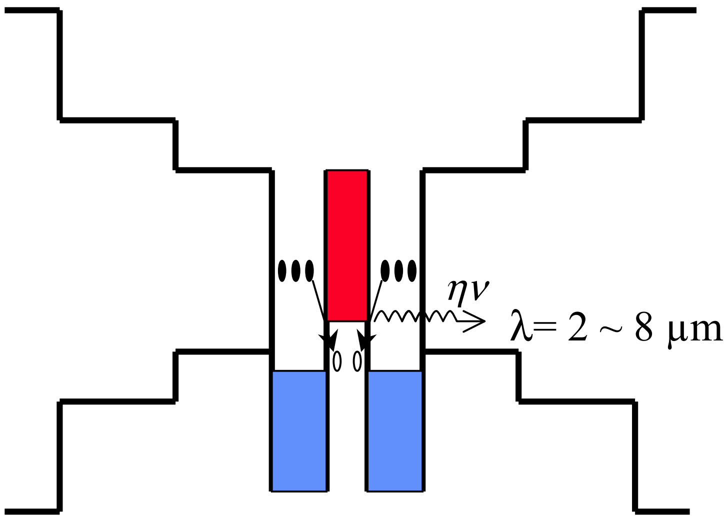
- $\Delta E_C = 2.3$ eV
- $\lambda = 4 - 12$ μm
- E(optic phonon) = 92 meV

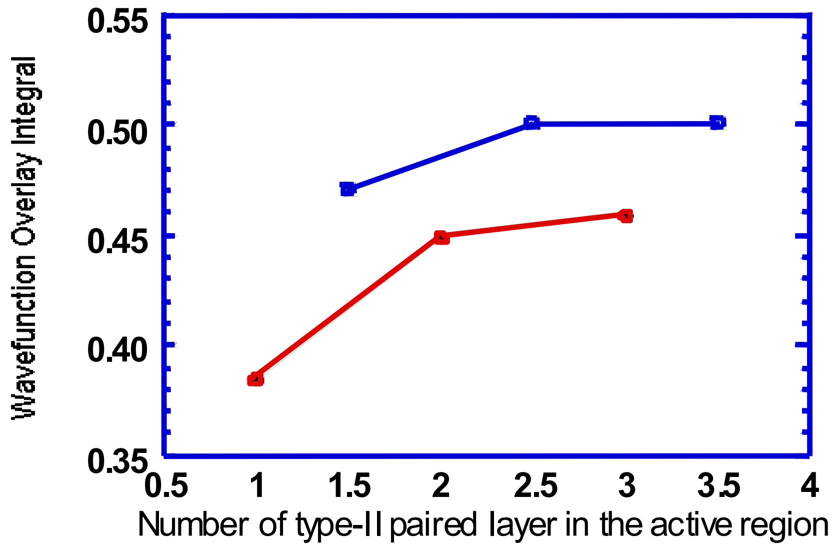
$\Rightarrow$ λ can be extended to 15 -30 μm

Type-II Sb-based QC laser

- Band structures and wave functions are solved self-consistently.
- The active region for one stage is modeled.

Band Structure Designs of Sb-Based Type-II W-Shape QW Mid-IR Lasers

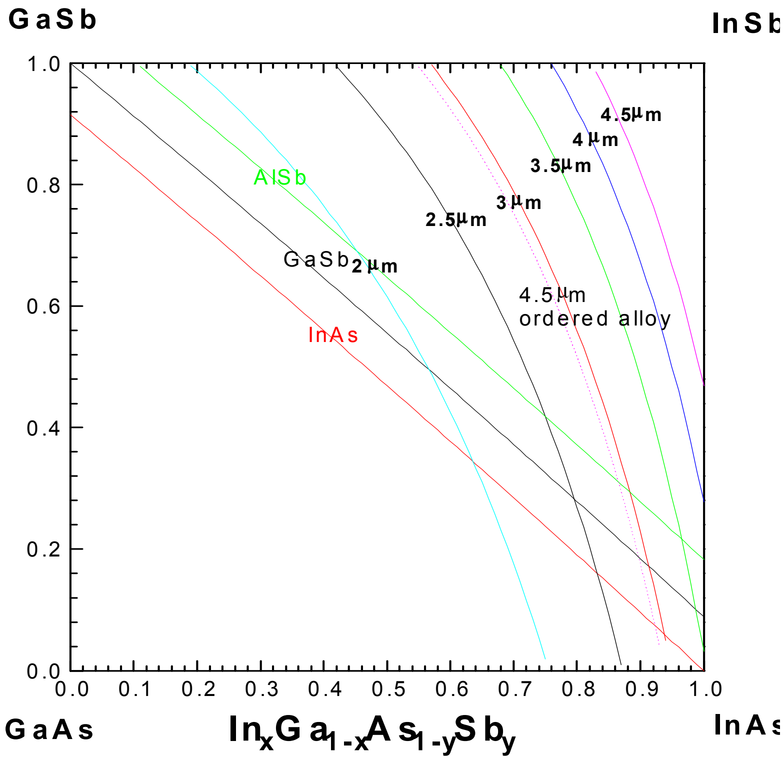


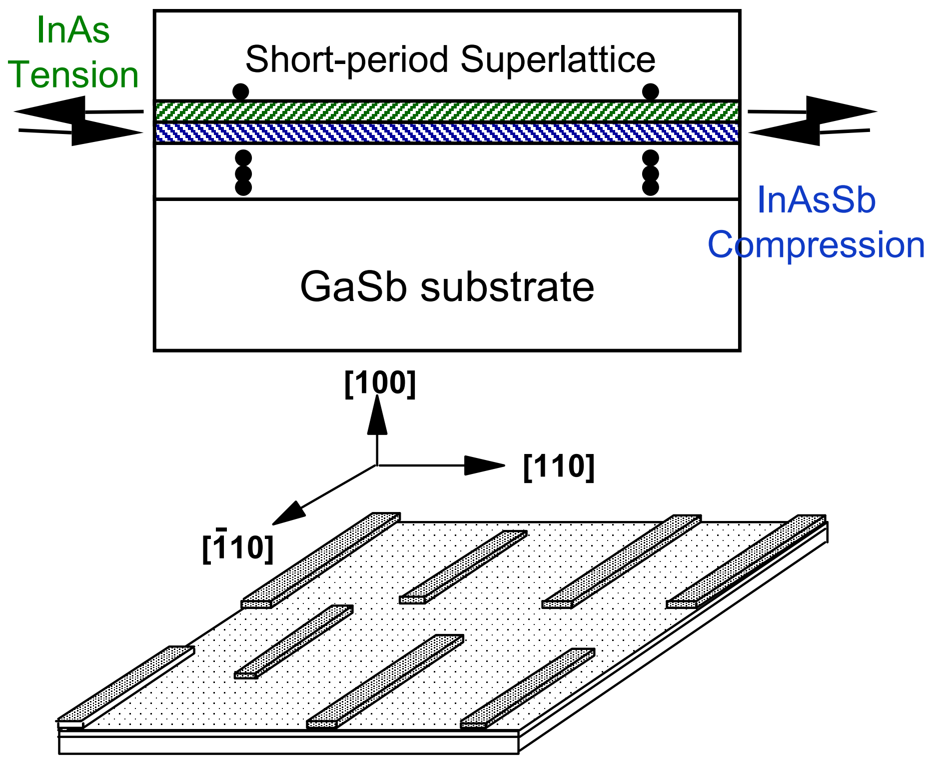


- MBE grown InAs/InGaAsSb/InAs type-II W-shape QW on GaSb substrates
- Minimized Auger recombination loss
- Electrons and holes confined in different layers

$\Rightarrow$ wave-function overlap is important

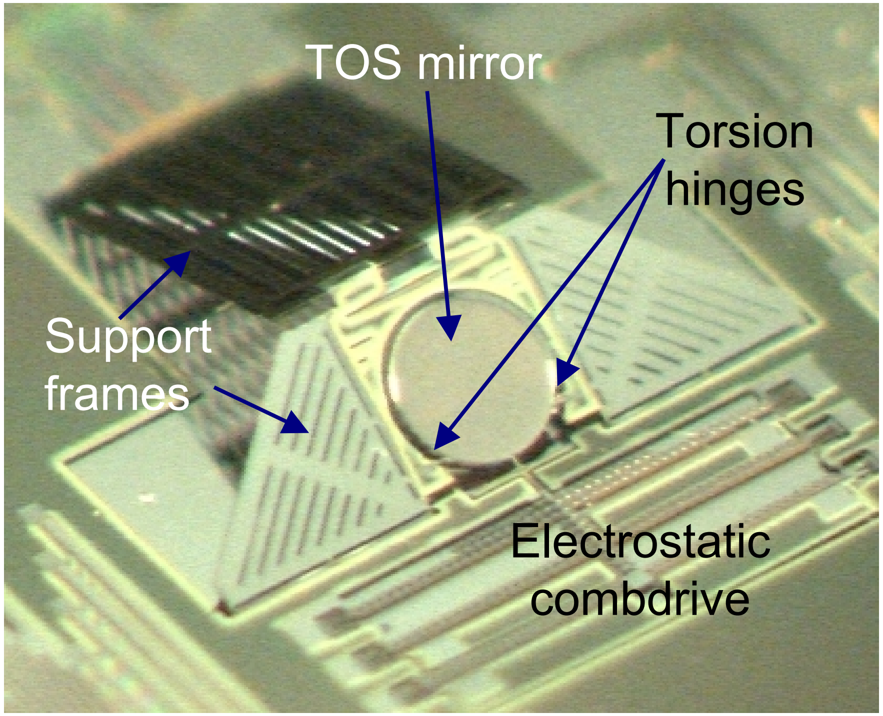
InGaAsSb Mid-IR Photodetector Materials with Extended Wavelength

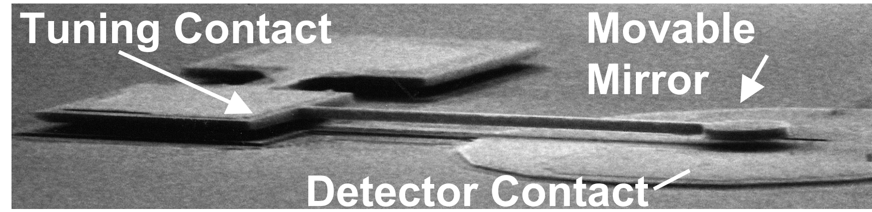


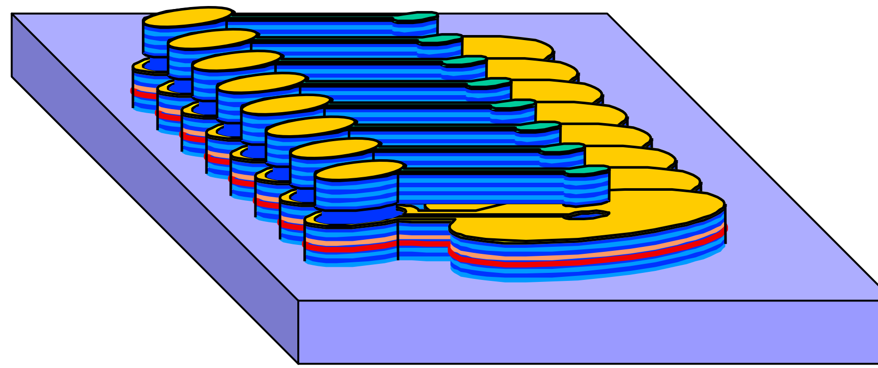


- Wavelength of 4.5 µm (the dotted curve) can be achieved in ordered InGaAsSb.
- $\lambda \geq 8$ µm can be achieved in GaInAsSb quantum wires using strain-balanced (InAs)/(InAsSb) short-period superlattice

MEMS Components for the Micro-FTIR System



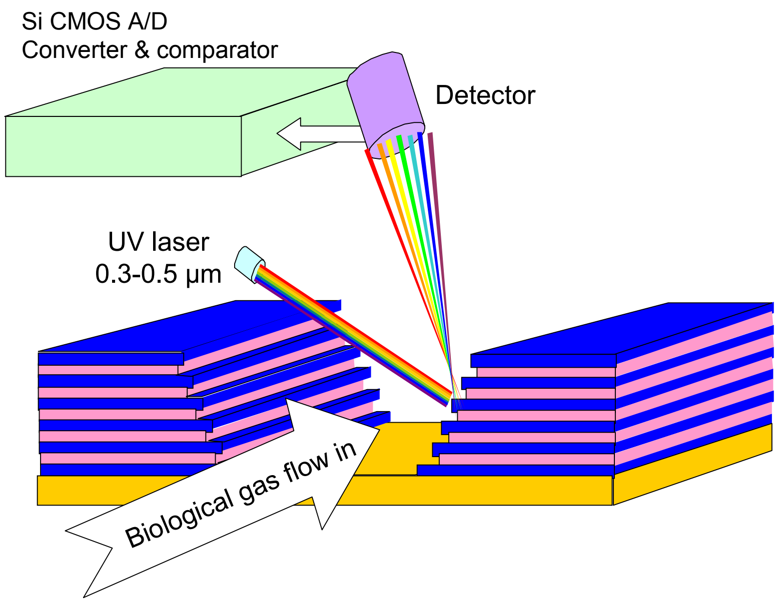


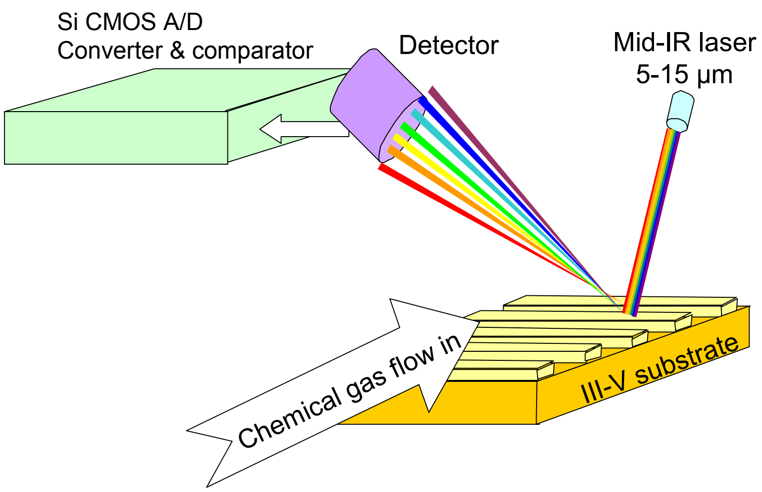


- TOS mirror structure after release and assembly.
- The mirror is mounted on support frames via torsion hinges
- Mirror is driven by an electrostatic comb drive.

- Wavelength tunable detector formed by a cantilever structure
- Array of MEMS tunable filters with integrated detectors to measure time- and spectrally- resolved fluorescence signals

Re-configurable MEMS Diffraction Grating Sensor Systems





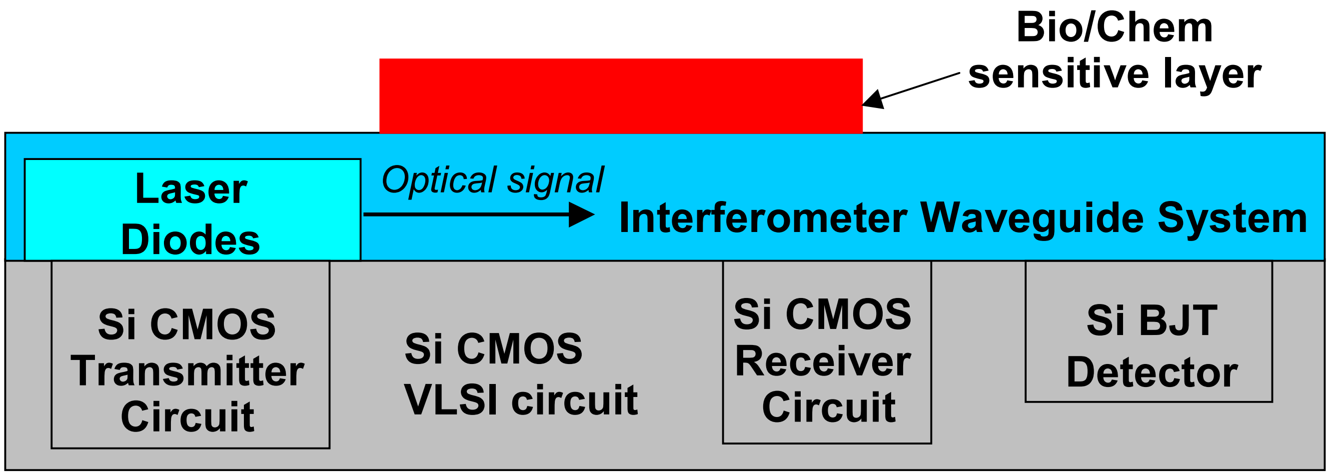
Superlattice UV Vertical Grating

- Vertical grating with a period of 100 nm
- InGaP/GaAs and AlGaAs/GaAs grown by MOCVD or MBE

Mid-IR Lateral Grating

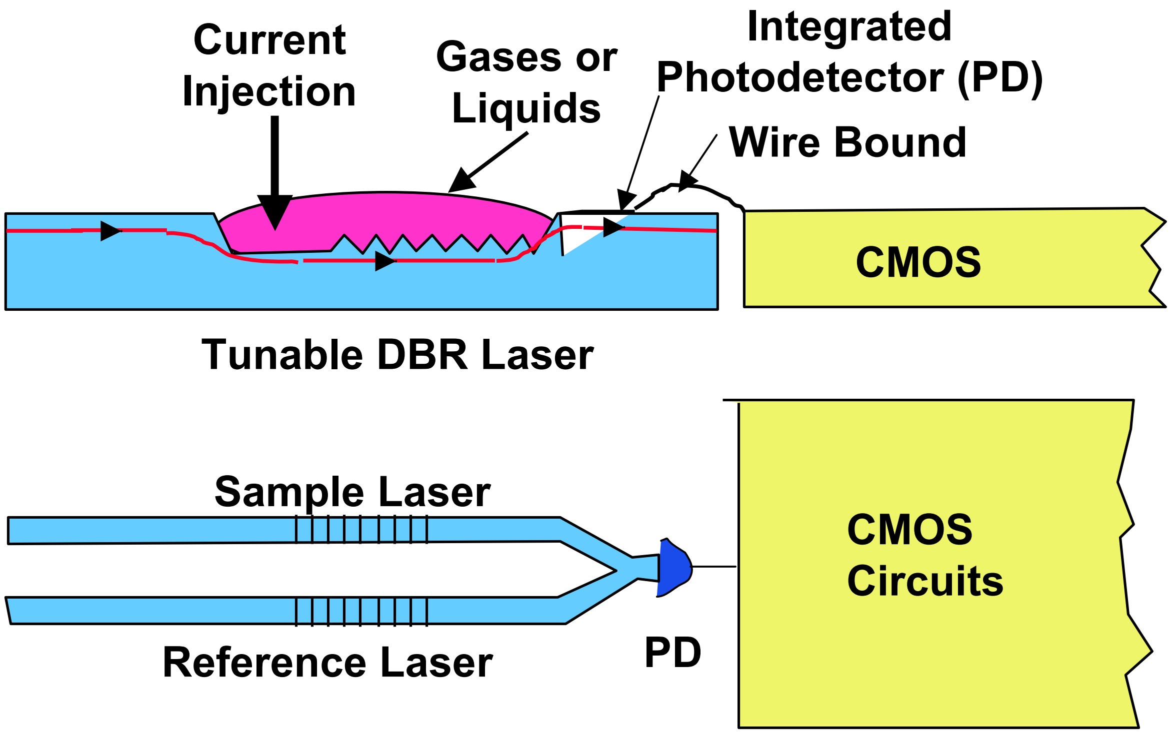
- Surface grating with a period of 200 nm
- Can be fabricated on a rotation stage using MEMS technology

Integrated Interferometer-Based *Aqueous* Bio-Sensor Systems



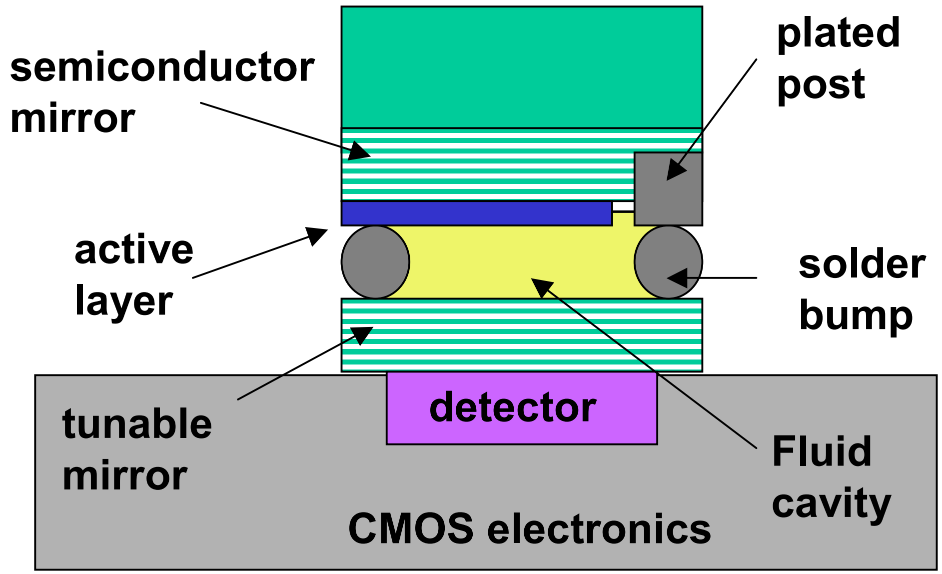
- Tunable laser diode-based interferometry.
- Utilizing passive or active bio/chem surface sensing layer.
- Detecting index of refraction change as small as 10^{-6}.
- Integrated with silicon-based electronics and photo-receiver circuits.

DBR laser-Based Interferometer with an Intra-Cavity Absorption Slot and a Detector



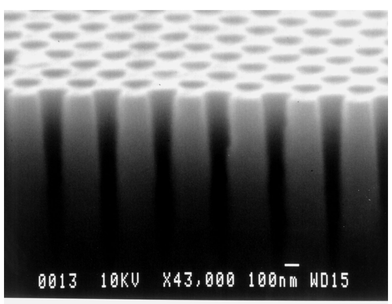
- Interference between two DBR lasers generates heterodyne beat on the detector
- High sensitivity ≈ change of index of refraction ≤ 10^{-6}
- Tunable light source

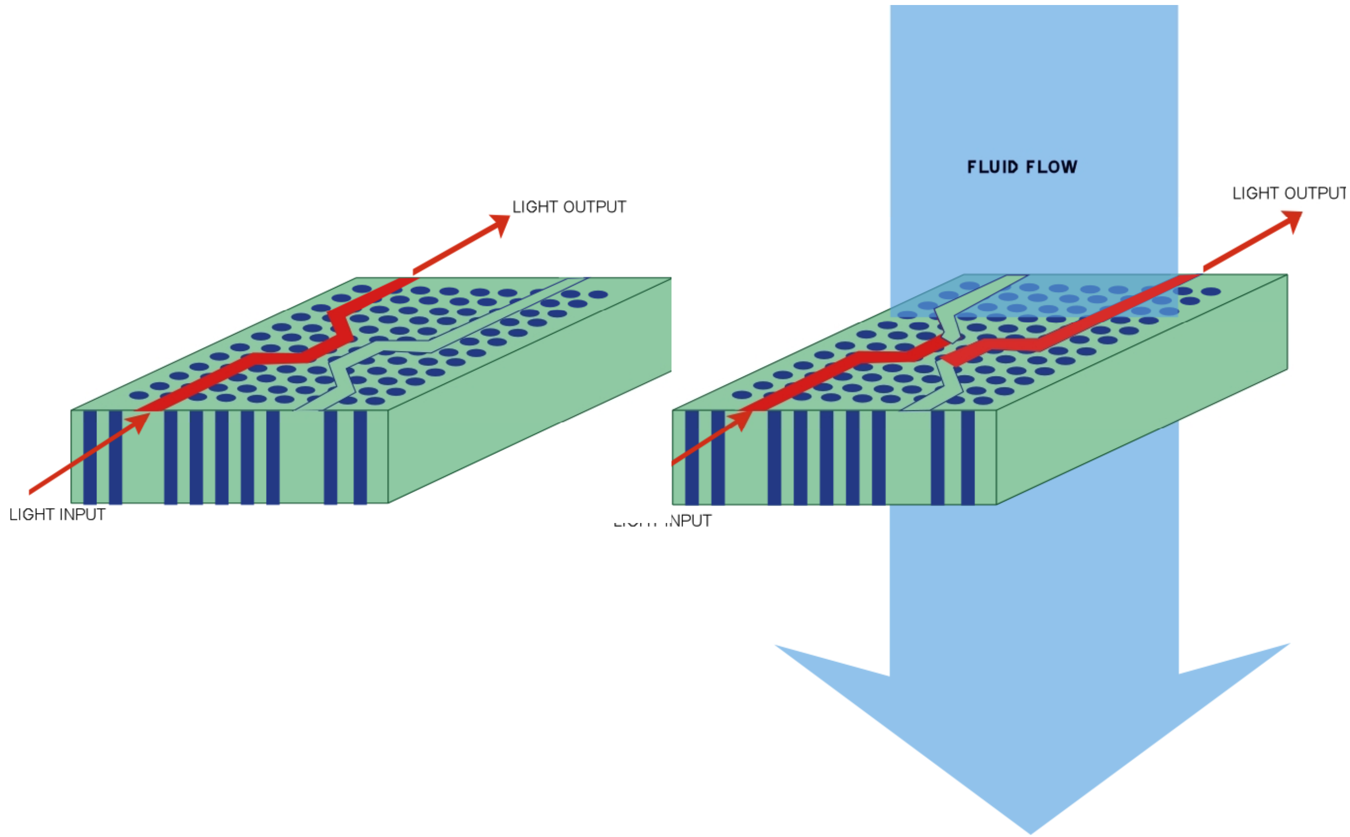
Fluidic Cavity VCSEL Interferometer



- Sample index and absorption modify the VCSEL output
- VCSEL array for different samples is possible
- Distinguish samples using wavelength tuning VCSELs

Microfluidic PBG Waveguide-Based Directional Coupler Bio-Sensors





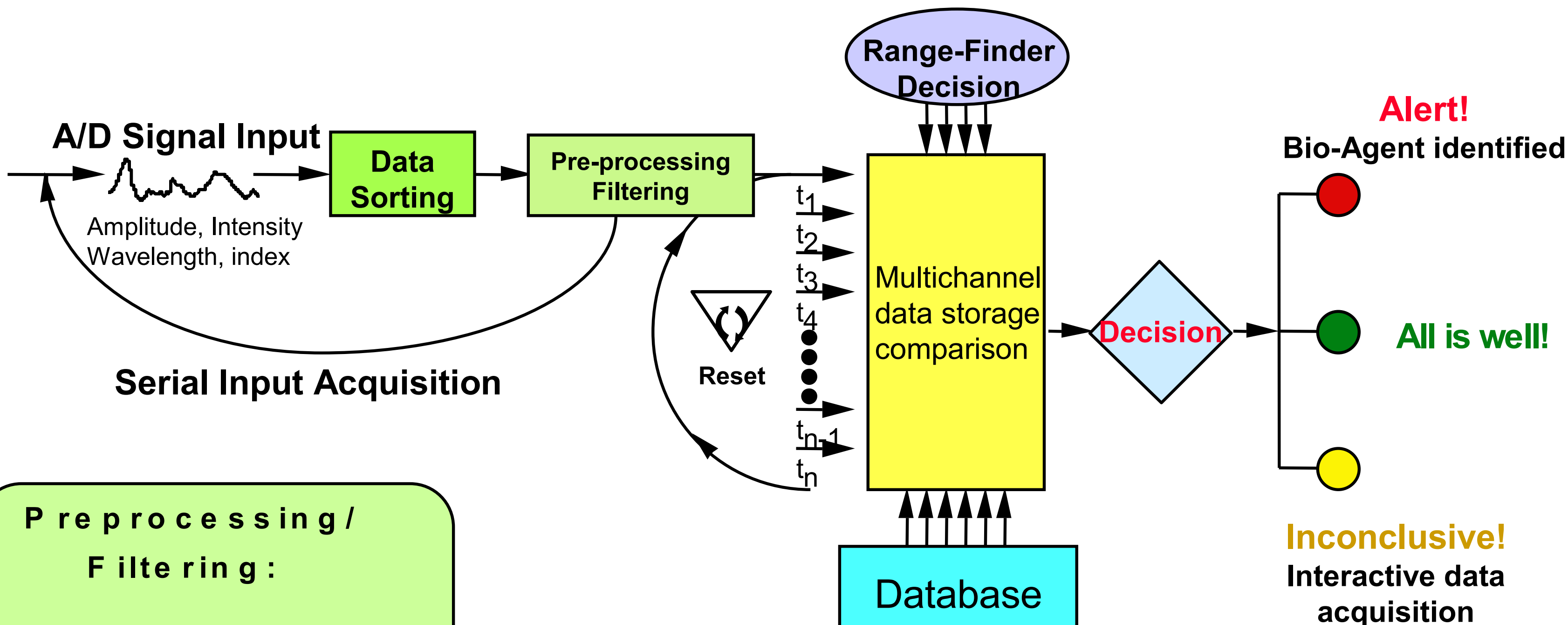
- 3D PBG formed in GaAs/AlGaAs QW by one-step epitaxy and processing
- Utilizing single or multiple ‘defect’ 3D-PBG to form photonic devices
- Two waveguide channels connected by a filter region
- Light switches through the filter when there is fluid presented

Heterogeneous Integration of Bio-Sensor Systems

- Information Fusion:
  - Develop effective optical signal processing and training algorithms using collected bioluminescence data
  - Develop and implement computer software into high-speed electronic circuits for on-chip target identification

- Hybrid Materials Integration:
  - Components - optoelectronic devices, MEMS spectrometer microsystems, signal processing electronics, Si CMOS circuits
  - Integration techniques - direct wafer bonding, thin-film transfer, flip-chip bump bonding

Data Acquisition and Information Fusion



Preprocessing/ Filtering:

Reduction or removal of noises in A/D signals induced by

1. Mechanical vibration of grating,spectrometer, reflecting morror.
2. Dynamic variation in concentration of bio-agents.

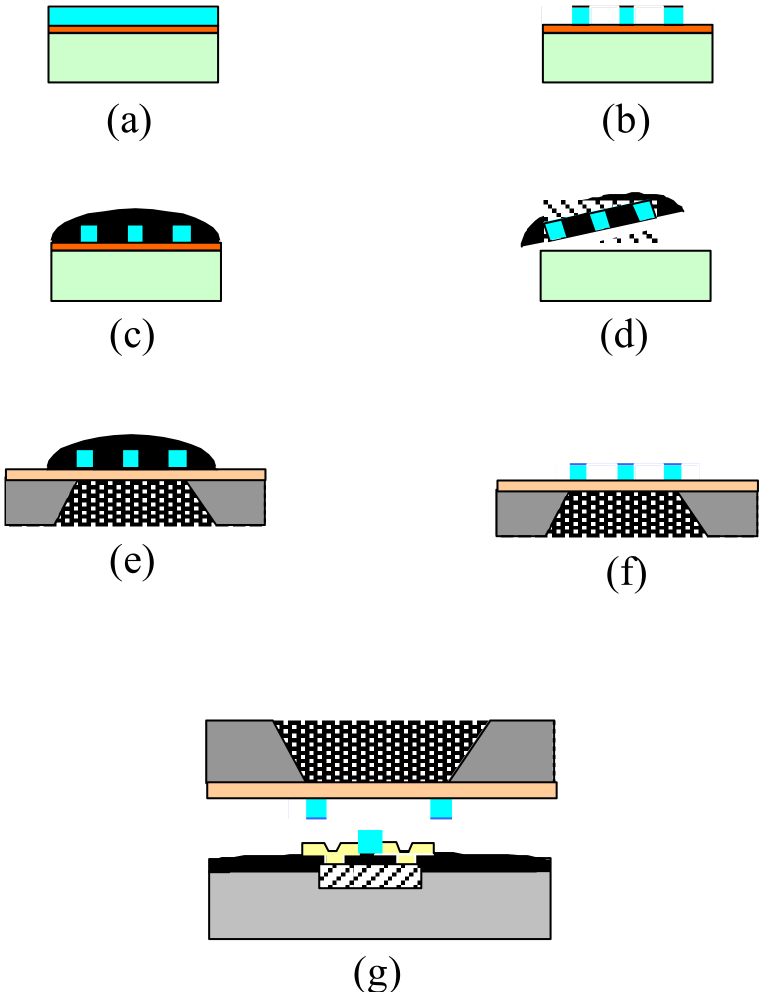
Range-finder Decision

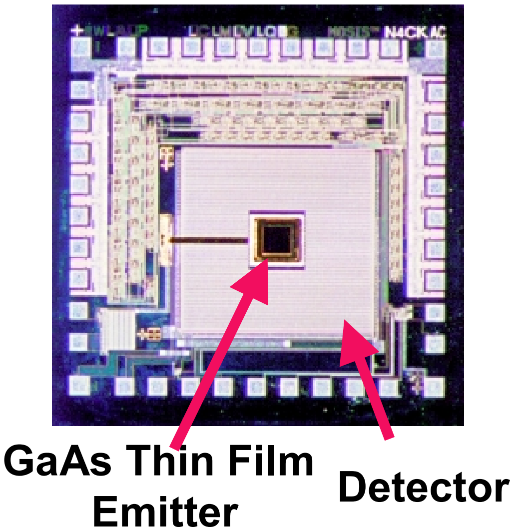
Decision made based on relaxed resolution to efficiently identify ranges of interest

Decision / Database

The probability distribution of the spectra of target bio-agents is modeled by Bayesian method and Artificial Neural Network

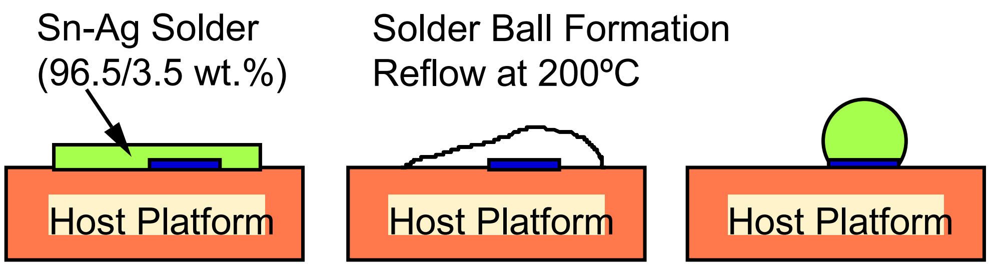
GaAs/Si Thin Film Integration Process

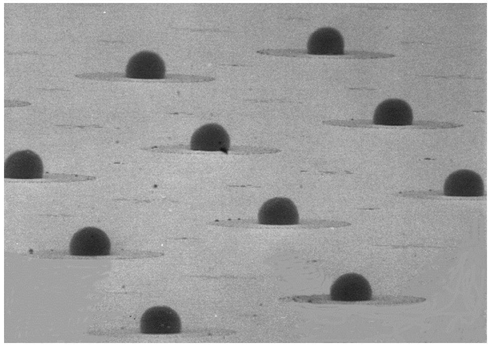




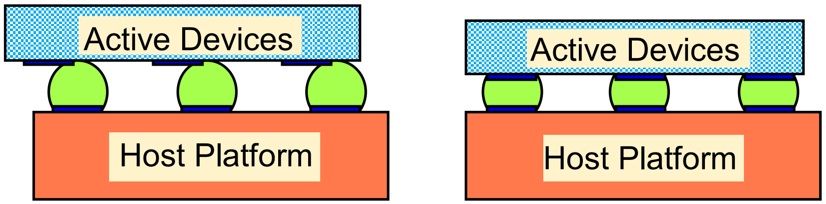
- Thin film GaAs emitter bonded in the middle of a Si CMOS BJT detector array, with Si CMOS analog and digital signal processing on-chip

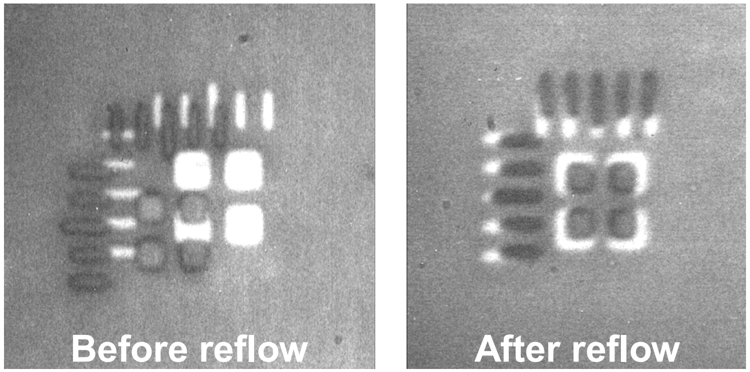
High Resolution Self-Aligned Flip-Chip Bonding Process





High Resolution Passive Self-Alignment Upon Reflow





- Solder materials: 96.5 wt. % Sn + 3.5 wt. % Ag
- Reflow at 200ºC to form solder balls
- Alignment resolution ≤ 0.25 µm

Institutional Contributions to Critical Center Research Plan

Technical Barrier	Research Plan	Team Members	Task
Bio-sensor architecture	• Bio-MEMS • Interferometer waveguide	Georgia Tech, Illinois	1, 2
UV (300 nm) laser diodes	GaN-based UV laser diodes	Texas, Illinois	1
Room temperature CW operation mid-IR laser diodes	• GaN- and Sb-based quantum cascade laser diodes • Sb-based type-II lasers • Ordered InGaAsSb detectors	Columbia, Illinois, Texas	1
Wide frequency range optical spectrometer system	• Re-configurable MEMS gratings • FTIR-on-a-chip • Tunable opto-MEMS detector arrays	Berkeley, Illinois	1
Integrated guided-wave interferometer systems	• DBR lasers with intracavity sampling • Tunable VCSELs with intracavity sampling • Micro-fluidic photonic bandgap waveguide	Maryland, Georgia Tech Colorado State Michigan	2
System integration	• Heterogeneous integration • Information fusion	Georgia Tech, Illinois & All Illinois	1, 2, 3

Management Structure of the BOSS Center

Research | ***Policy and Plans*** | ***Infrastructure***

Advisory Committee

Executive Committee
Director
K. Y. Cheng
Associate Directors
M. Feng
N. Jokerst

Program Committee

Office of the Director

µ-Spectrometer-Sensor
R. Dupuis

Interferometer-Sensor
P. Bhattacharya

Heterogeneous Integration
K. Hsieh